High resolution infrared absorption spectroscopy of ions of astrophysical interest: $^{36}ArH^+$ and $^{38}ArH^+$

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Abstract

- $^{36}ArH^+$ and $^{38}ArH^+$ have been recently identified by their rotational emissions in the Crab Nebula [1] and the interstellar media [2] from sub-mm spectra obtained with the Herschel Space Observatory. ArH^+ is the first noble gas compound observed hitherto in space. Given the atmospheric opacity at these sub-mm frequencies and the current lack of appropriate space telescopes after the recent end of the Herschel mission on Spring 2013, future studies of these ions will rely on ground-based IR observations. Incidentally, the Ar isotopic composition in the interstellar media is ^{40}Ar/ ^{38}Ar/ $^{\mathbf{36}}$**Ar** = 0.0 / 15.0 / **85.0** %, but in the Earth's atmosphere it is: $^{\mathbf{40}}$**Ar**/ ^{38}Ar/ ^{36}Ar = **99.6** / 0.06 / 0.34 %; where ^{40}Ar is mainly produced by ^{40}K decay ($\tau_{1/2}$ = 1.25 × 10^9 years).
- In laboratories, ArH^+ can be efficiently produced in H_2 + Ar low pressure plasmas [3,4], but its density depends strongly on the discharge conditions.
- In this work, the high resolution IR absorption spectra of $^{36}ArH^+$ and $^{38}ArH^+$ generated in a low pressure hollow cathode discharge have been measured with a difference frequency laser spectrometer. Accurate wavenumbers of 19 ro-vibrational lines of the v = 1–0 band in the range 4.1–3.7 μm (2450–2715 cm^{-1}) have been obtained. Of those, only eight had been reported before, and with much larger uncertainty. The results will be useful for further astrophysical searches of these ions.

Experimental System

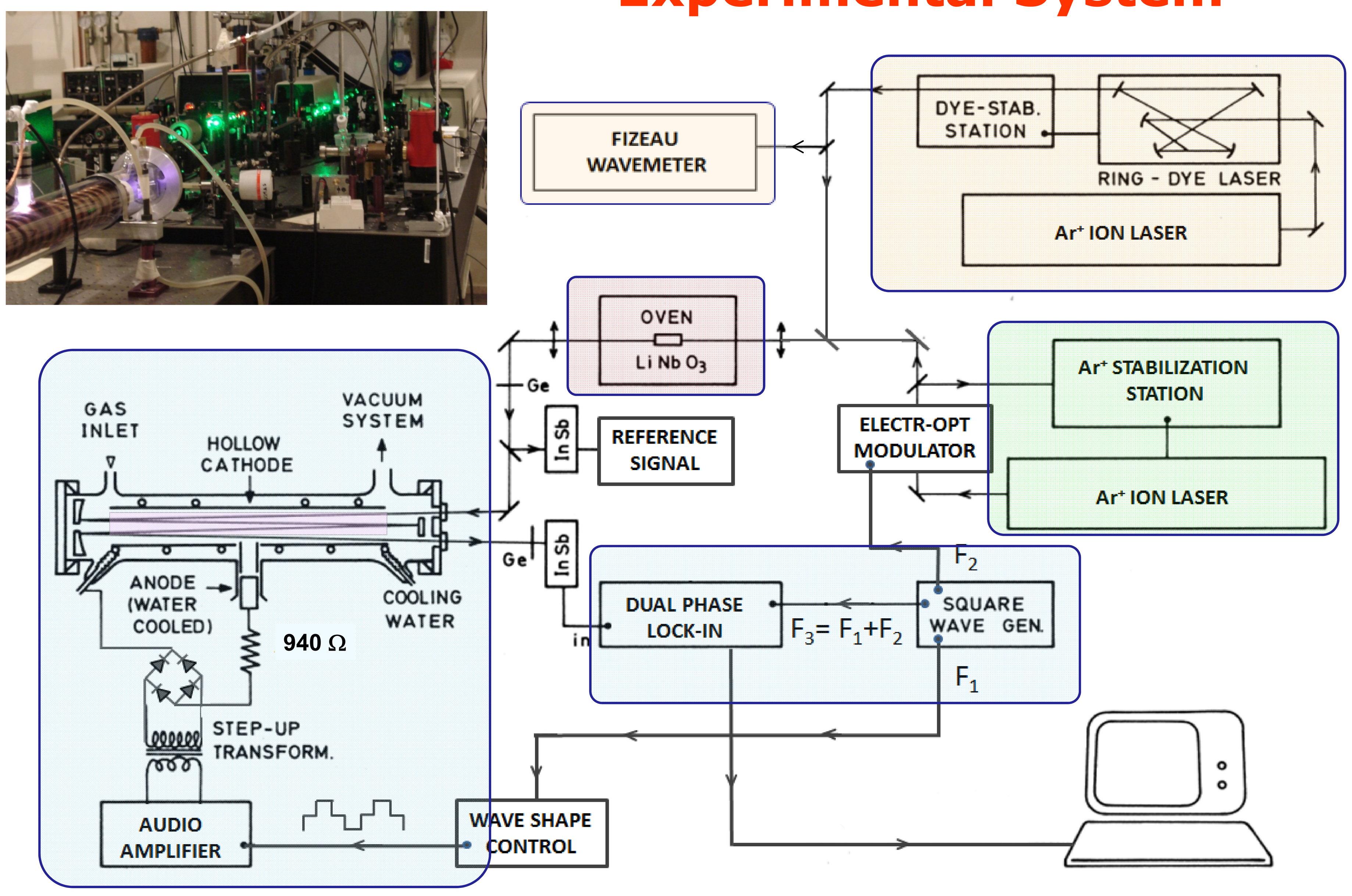

Fig. 1 Experimental Set-up

PLASMA GENERATION

A hollow cathode discharge reactor with White-cell multipass configuration (laser path-length = 22.4 m) was used. Its description is found elsewhere [5].

Pure Ar flow at 0.4 mbar in its natural isotopic composition is used to generate $^{40}ArH^+$, $^{38}ArH^+$, $^{36}ArH^+$. Attempts to increase the ArH^+ IR absorptions by adding H_2 failed, indicating that tiny amounts of H_2 are necessary to optimize ArH^+ concentrations.

Recent experiments on the kinetics at different Ar/H_2 mole fractions and pressures suggest that electron temperature and H_3^+ excitation (through the balance of the reaction $H_3^+ + Ar \rightleftarrows ArH^+ + H_2$ [6]) have a drastic effect on ArH^+ concentration.

DIFFERENCE FREQUENCY LASER SPECTROMETER

The tunable IR radiation is generated by mixing the outputs of an Ar^+ laser and a tunable ring dye laser in a $LiNbO_3$ crystal contained in a temperature-controlled oven. The Ar^+ laser is frequency stabilized with high precision and accuracy (Δν < 1 MHz). A wavemeter is used to measure the dye laser wavelength at each point of the spectrum. The wavelength coverage is ~2.2–4.2 μm, with ~3MHz linewidth and ~5 μW power.

Amplitude modulation of the discharge and the laser at different frequencies and detection at the sum frequency with an autobalanced subtractive amplifier markedly increase sensitivity. The apparatus has been recently used to confirm the identification of NH_3D^+ in space [5,7].

IR ArH^+ spectroscopy

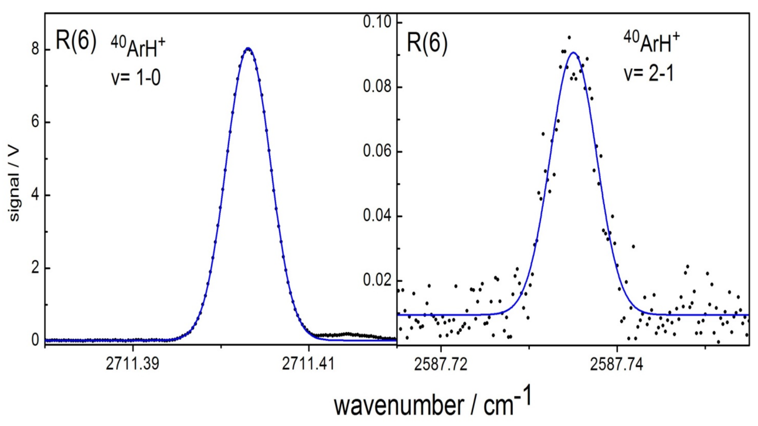

Fig.2 *$^{40}ArH^+$ lines*

Signal/Noise R_6(1-0)~1100 (1 scan)

Linestrength ⇒[$^{40}ArH^+$]≈3x10^{10} cm^{-3}

Linewidth ⇒ T_{kin} = T_{rot} = 390±10 K

I(v=1-0)/I(v=2-1) ⇒ T_{vib} ≈ 580 K

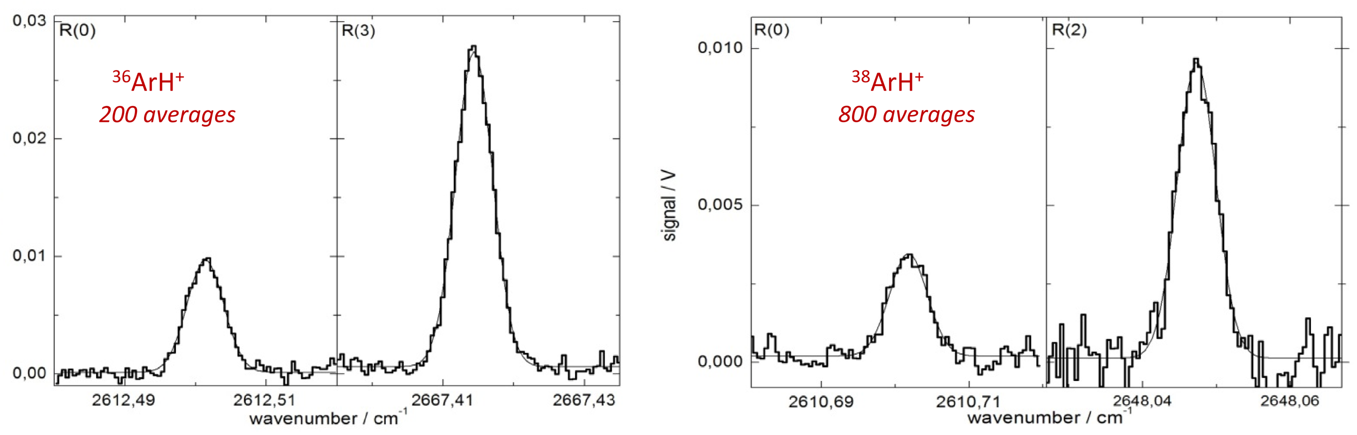

Fig.3 *$^{36}ArH^+$ and $^{38}ArH^+$ lines*

Table 1 *$^{36}ArH^+$ and $^{38}ArH^+$ observed line-centers with 1σ uncertainties, and spectroscopic constants of $^{36}ArH^+$*

Isotopologue	Line	ν_{obs} (cm^{-1})	σ^a	$(O-C)^b$	Constant^c (cm^{-1})	
$^{36}ArH^+$	P(6)	2458.36336	11.4	0.3	B_0	10.30044364(778)
	P(5)	2482.47613	11.3	−5.5	D_0	6.21374(154) × 10^{-4}
	P(4)	2505.91727	10.5	7.7	ν_1	2592.651339(42)
	P(3)	2528.67068	11.6	3.8	B_1	9.92620133(616)
	P(2)	2550.72091	11.8	−8.9	D_1	6.127689(908) × 10^{-4}
	P(1)	2572.05291	13.2	−2.8		
	R(0)	2612.50135	11.3	5.9		
	R(1)	2631.58798	11.1	−10.6		
	R(2)	2649.89731	10.3	8.6		
	R(3)	2667.41441	10.4	−0.3		
	R(4)	2684.12561	11.9	4.6		
	R(5)	2700.01671	11.4	−8.8		
	R(6)	2715.07445	11.3	0.9		
	R(7)	2729.28504	11.0	2.0		
$^{38}ArH^+$	R(0)	2610.70177	13.9			
	R(1)	2629.76268	11.2			
	R(2)	2648.04731	13.4			
	R(3)	2665.54197	14.9			
	R(4)	2682.23225	13.9			

Notes.
^{a} σ = estimated uncertainty/10^{-5} cm^{-1}.
^{b} $(O-C)=(\nu_{obs}-\nu_{calc})/10^{-5}$ cm^{-1}.
^{c} Numbers in parentheses are one standard deviation in units of the last quoted digit, as derived from the fit.

Summary & Conclusions

Accurate wavenumbers for 19 vibration-rotation lines of $^{36}ArH^+$ and $^{38}ArH^+$ have been measured [8]. Only 8 of them had been reported before, and with much less accuracy.

The new wavenumbers have improved the Dunham-type fit to the published rotation and vib-rotation data for all isotopologues of ArH^+, allowing more accurate predictions of other transitions for any of them.

The present data should help in future searches of $^{38}ArH^+$ and $^{36}ArH^+$ in space. They should be detectable in absorption in dark clouds for column densities >10^{13} cm^{-2} at T<100 K against bright IR sources, and in emission if T_{kin} > 1000 K, like possibly in the knots of the Crab nebula.

References

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